Constellation Observing System for Meteorology, Ionosphere, and Climate: A Joint Taiwan-U.S. Space Mission for Atmospheric and Geodetic Sciences

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A joint Taiwan-U.S. scientific satellite project began formally with the signing of a bilateral Cooperative Agreement in December 1997. Named COSMIC—Constellation Observing System for Meteorology, Ionosphere and Climate, the project consists of a constellation of eight low-Earth-orbit micro-satellites to be launched in 2003. Each of the micro-satellites will carry an advanced GPS (Global Positioning System) receiver, a Tiny Ionospheric Photometer and a tri-band beacon transmitter. The satellites will conduct atmospheric vertical profile soundings for meteorology, climate, and ionospheric research using GPS radio signals received minutes before a GPS satellite gets occulted by the Earth from the line-of-sight of any of the micro-satellites. COSMIC will produce approximately 4,000 globally uniform, all-weather soundings per day. Also, the routine GPS tracking of the COSMIC satellite orbits will provide new data for improving the solution of Earth's gravity field.

Introduction

The technique of atmospheric limb sounding by radio occultation was first developed in the 1960s and since used to study planetary atmospheres. Applying this technique to the Earth's atmosphere using the Global Positioning System (GPS) as a source and a receiver in low-Earth orbit was suggested as early as 1988 [*Yunck et al.*, 1988], but was not tested until April 1, 1995, when a proof-of-concept, experimental satellite known as MicroLab-1 was launched into low Earth orbit to test the technique [*Ware et al.*, 1996]. Costing only $10 million, this GPS/METerology experiment was primarily supported by the National Science Foundation and carried out by the University Corporation for Atmospheric Research (UCAR) with main instrumentation provided by NASA's Jet Propulsion Laboratory (JPL).

The technique takes advantage of our precise knowledge about GPS satellite positions (in high Earth orbits) and timing of GPS radio signals. The experimental instrument on MicroLab-1 (in a low-Earth-orbit, or LEO) measured the extra time it takes for a GPS signal to enter Earth's atmosphere obliquely, pass through, and reemerge to strike the LEO satellite, compared to an otherwise un-refracted direct ray path. The evolving time delays of the GPS signal due to such atmospheric passage during the occultation are used to derive the corresponding bending angles of the ray path, which in turn are converted to the refractive index profile of the atmosphere (using, for example, the Abelian transformation). From the refractive index profile one can retrieve important weather and climate research parameters including atmospheric temperature, moisture, and pressure at the vicinity of the ray's tangent point to the Earth.. With each occultation lasting only 1-2 minutes, a LEO satellite can track approximately 500 radio occultation soundings per day (including both rising and setting occultations). The atmospheric profile data can then be processed and assimilated by computer forecast models that guide, for example, day-to-day weather predictions [*Kuo et al.*, 1997]. The radio occultation sounding also measures electron density in the ionosphere, which is of great interest to ionospheric research and space weather monitoring. For a more detailed discussion of the technique and its scientific observables, see *Melbourne et al.* [1994].

Over a two-year period between April 1995 through April 1997, over 62,000 radio occultation soundings have been collected by MicroLab-1. The data from the GPS/MET proof-of-concept experiment has stimulated broad international research to verify the accuracy and utility of the data [*Ware et al*., 1996; *Kursinski et al*., 1996; *Leroy*, 1997; *Kuo et al*., 1998; Hajj and Romans, 1998]. While these data compare very favorably with other data [*Rocken et al.*, 1997; *Kursinski et al.*, 1997], a single experimental satellite with one instrument collecting a few hundred profiles daily is far from sufficient to meet the requirements of global atmospheric research and prediction.

Thus a conceptual design of a constellation of LEO satellites was started at UCAR to exploit the full potential of radio occultation sounding techniques, which led to the development of COSMIC---Constellation Observing System for Meteorology, Ionosphere and Climate. In a nutshell, the COSMIC constellation utilizes the same technique as GPS/MET, but with eight-fold the amount of data with higher data quality. It also provides additional observations for ionosphere and geodesy. Taking full advantage of this new observational tool, COSMIC promises to deliver not only useful data for Earth scientific research, but also “snapshots” for near real-time applications such as weather prediction, space weather, and aviation.

COSMIC Mission Scenario

The total cost of COSMIC including the pre-launch spacecraft development, launch service, plus the first two years of post-launch operation is estimated to be roughly $100 million. Because of COSMIC’s scientific, technical, and educational merits, the National Science Council of Taiwan, Republic of China, has committed approximately $80 million for the project. The remaining 20% will be funded by the participating U.S. agencies, including NSF, NASA, NOAA, Navy and Air Force. COSMIC will be jointly implemented by UCAR and Taiwan’s National Space Program Office, with the participation of JPL, U.S. Naval Research Laboratory, the University of Arizona, Florida State University, and the University of Texas. COSMIC represents the third space mission of Taiwan, and is also named ROCSAT-3 (Republic Of China, SATellite mission #3) in Taiwan.

The eight micro-satellites will be launched using one rocket in early 2003 into an initial orbit at 400-km altitude and an inclination of about 72 degrees. Then different satellites will be boosted by on-board thrusters to different altitudes ranging from 400 to 800 km. The corresponding different rate of orbit nodal precession will then gradually drift the orbit planes apart, until a more-or-less even distribution of the eight orbit planes is achieved. This will take about a year, during which time the satellites will already start collecting atmospheric soundings (although the data are not as uniformly distributed during this phase, see below) and critical geodetic/gravity data. At the end of this orbit-adjusting phase all eight satellites will be raised to the same altitude of about 800 km, thus begin the normal operation phase. The final operational configuration is depicted in Figure 1.

The COSMIC mission is designed for two years of operation. However, the on-board consumables are sized for five years of operation. The actual lifetime of the satellites will depend on the instrument condition, orbit stability, and the condition of the spacecraft. It is anticipated that COSMIC will be followed with operational constellations currently being planned in the U.S. and

Europe. We anticipate that COSMIC-type radio occultation soundings will become available on a routine basis in the future.

When stowed for launch, each micro-satellite will be a cylinder, approximately 126 centimeters in diameter by 46 cm deep, and will weigh about 50 kilograms. Figure 2 gives an artist's conception of one spacecraft after deployment. The constellation of eight satellites will gather more than 4,000 vertical sounding profiles per day; a typical daily sampling is shown in Figure 3. It covers the oceans as densely as land areas, including traditionally data-sparse oceanic and polar regions, thanks to the even distribution of COSMIC as well as GPS orbits. These radio occultation soundings are not affected by clouds, aerosol or precipitation -- an important advantage over other remote sensing methods based on radiometric techniques. For comparison, the loci of the current operational radiosonde network are also given in Fig. 3 (shown as red dots).

It is proposed that the ground segment of COSMIC consists of: (1) a satellite operations control center in Taiwan; (2) two Data Analysis and Archive Centers, one in Taipei, Taiwan, and one in Boulder, Colorado; and (3) a global ground fiducial and beacon network built upon existing NASA and international network. In general, all the data will be made available openly and freely (or at nominal costs of reproduction and distribution) to the international scientific and operational communities. It is expected that the data will be sent to and processed by the Data Analysis and Archive Centers continuously, with data latency time no more than 90 minutes for regional and global numerical weather prediction. This is particularly important because advanced (and computationally demanding) data assimilation systems are needed to make optimal use of the COSMIC data for weather prediction. The operational ionospheric products also require data latency to be no more than two hours, to be useful for space-weather monitoring and nowcasting. The ionospheric scintillation data will be modulated and transmitted by the tri-band beacon transmitter, and relayed to the Data Analysis and Archive Centers, allowing the monitoring of space weather with a data latency of 5~10 minutes.

While it is highly desirable to have the maximum number of satellites and longest lifetime possible, many trade-offs in mission design and orbit scenarios are being considered to reconcile various scientific requirements and financial and logistic constraints.

COSMIC Measurements and Science

What are the COSMIC measurements and data products that will be useful for scientific research and near real-time applications? Over 100 scientists, engineers and instrument experts gathered at the first Taiwan-U.S. Bilateral COSMIC Science Workshop held in Taiwan during February 26-28, 1998, to discuss and define the COSMIC science. Four scientific working groups were formed: Meteorology, Climate, Ionosphere, and Geodesy/Gravity:

<u>Meteorology</u>: Water vapor and its phase changes are major drivers for weather and climate, and 90% of the water vapor resides within the bottom 3 km of the atmosphere. A fundamental problem in meteorology and weather prediction is an accurate measurement of water vapor and its distribution. The atmospheric refractivity profile derived from COSMIC observables is a function of temperature and water vapor. Therefore, this is a closure problem of one equation with two unknowns. Recent studies have shown that given accurate determination of refractivity, water vapor may be calculated using an independent estimate of temperature. This calculation is relatively insensitive to small uncertainties in the temperature. For example, in the lower troposphere, water vapor pressure may be estimated to within 0.5 mb if the temperature is known to within 2°K [*Ware et al.*, 1996].

Alternatively, the bending angle (or refractivity) data derived from the raw COSMIC measurements may be assimilated directly into numerical models. Recent numerical experiments have shown that refractivity or bending angle assimilation can substantially improve the quality of temperature and water vapor analysis for a weather prediction model [*Kuo et al*., 1997; *Zou et al*., 1999].

An advanced version of the GPS/MET instrument for COSMIC with a higher-gain antenna and improved firmware will be built , and open-loop tracking procedure and advanced data retrieval techniques developed at JPL. It is anticipated that 90% of the soundings could reach to within 1 km above the surface, deeper than typical MicroLab-1 penetrations. Typical vertical resolution of the measurement ranges from 200 m to 1 km.

The high vertical-resolution GPS radio occultation soundings complement the high horizontal resolution of traditional radiometric satellite soundings (such as GOES, SSM/I, and TOVS). Assimilating data from different remote sensing and traditional observing systems as well as ground-based GPS occultation sounding data will make possible improved description of the 3-D structure of atmospheric temperature and water vapor content, leading to improved weather prediction on both global and regional scales.

<u>Climate</u>: One unique aspect of radio occultation sounding based on precise measurements of the radio frequency and its phase shift is the "self-calibrating" nature, as each measurement is independent of the others. Unlike the traditional satellite microwave measurements, the radio soundings have no instrument drift problem. Climate research will benefit strongly from the large amount and global coverage of the COSMIC soundings. It will establish a global climate change "thermometer" which has unprecedented long-term stability, if given a long operation period, providing a global self-calibrating data set for climate monitoring and model testing. In particular, the fact that COSMIC data require no calibration offers a unique opportunity for the climate community to study subtle climate changes at a much higher accuracy and vertical resolution than currently feasible. Specific applications include the studies of water vapor distribution, especially in the tropics; ozone depletion; troposphere/stratosphere exchange; and volcanic effects.

<u>Ionosphere</u>: COSMIC's advanced GPS receiver instruments will observe the ionosphere at a temporal and spatial resolution that is unprecedented. In addition, two other ionospheric instruments will be put onboard each COSMIC satellite (cf. Figure 2): a Tiny Ionospheric Photometer (to be built at the Naval Research Laboratory) and a tri-band beacon transmitter (to be developed jointly by the Naval Research Laboratory and the Applied Research Laboratory of University of Texas, Austin). They provide two-dimensional horizontal mapping of electron density, complementing the GPS radio occultation soundings so that three-dimensional, time-varying fields of electron density between 90 and 800 km can be inferred. Such advances should lead to better understanding of the effects of solar storms, and hence better "space-weather" monitoring and forecasting capabilities. The solar storms inject huge numbers of high-energy particles into Earth's upper atmosphere, jeopardizing power grids and high-frequency communications on Earth as well as communication satellites in space. In addition, each of the eight micro-satellites carries a magnetometers to measure the global distribution of field-aligned electric currents and the size of auroral oval in the polar ionosphere.

<u>Geodesy/Gravity</u>: COSMIC represents the first time a large amount of continuous, uniform, and precise GPS tracking of satellite orbits will be available. Known as the high-low satellite-satellite tracking, this technique has in the past already yielded valuable data for improved solution of Earth's

gravity field [e.g., *Lemoine et al*., 1998]. In the case of COSMIC, the GPS occultation signals are actually less useful for the gravity purpose as they are “contaminated” by the atmosphere. The most useful tracking data for the gravity purpose are the bulk of the routine GPS tracking of the COSMIC satellites (at no more than 1 Hertz sampling rate, as opposed to up to 100 Hertz during an occultation). Such tracking data during the operation phase (at final 800-km high orbits) can yield useful solutions of temporal variations of the low-degree gravity field, while at the same time help improve the orbit determination for GPS satellite themselves. The stronger benefit, however, comes from the initial orbit-adjusting phase when the orbits are lower in altitude and the non-gravitational drag effect largely cancels between two satellites flying in tandem during this period. Simulations [*Chao et al.*, 1999] have shown that using these tracking data it is possible to improve our knowledge of Earth’s low-degree gravity field by up to an order-of-magnitude.

Epilogue

Consisting of a constellation of eight micro-satellites making use of GPS occultation and tracking signals, the COSMIC mission promises to deliver a large amount of useful data for meteorology, climate, ionospheric, and geodetic research as well as for operational weather forecasting and space weather monitoring. The technique attests to the doctrine “one person’s noise may be another person’s signal,” and represents a prime example where a technique originally developed for one application, in this case geodesy, finds fundamental applications in various other disciplines. It is important to recognize that retrieving detailed three-dimensional water vapor distribution from the COSMIC-type radio occultation data remains a challenge. It is hoped that with the improved instrument development, receiver firmware, open-loop tracking procedure, and advanced data assimilation technique COSMIC will provide valuable data sets to enable significant advances in this research.

In addition to the co-authors of this article, many people in Taiwan and the U.S. have contributed to the inception and definition of the COSMIC Mission. To disseminate the latest information, the COSMIC project maintains a website at URL: <http://www.cosmic.ucar.edu>.

References

Chao, B. F., E. C. Pavlis, C. W. Huang, C. C. Liu, C. K. Shum C. L. Tseng, and M. Yang, COSMIC: Improving Earth’s gravity model and other geodetic applications, submitted, *Terr. Atmos. and Ocean. Sc.*, 1999.

Hajj, G. A. and L. J. Romans, Ionospheric electron density profiles obtained with the GPS: Results from the GPS/MET experiment, *Radio Science, 33*, No. 1, pp 175-190, 1998.

Kuo, Y.-H., X. Zou, and W. Huang, The impact of GPS data on the prediction of an extratropical cyclone: An observing system simulation experiment. *J. Dyn. Atmos. Ocean, 27*, 439-470, 1997.

Kursinski, E.R., G.A. Hajj, J.T. Schofield, R.P. Linfield and K.R. Hardy, Observing Earth's atmosphere with radio occultation measurements using the Global Positioning System. *J. Geophys. Res., 102*, 23,429-23,465, 1997.

Lemoine, F. G., N. K. Pavlis, S. C. Kenyon, R. H. Rapp, E. C. Pavlis, and B. F. Chao, New high-resolution model developed for Earth's gravitational field, *EOS, Trans. Amer. Geophys. Union 79,* 113-118, 1998.

Leroy, S., The measurement of geopotential heights by GPS radio occultation, *Jour. Geophysical Res., 102*, 6971-6986, 1997.

Melbourne, W. G. E.S Davis, C.B. Duncan, G.A. Hajj, K. R. Hardy, E.R. Kursinski, T.K. Meehan, L.E. Young, T.P. Yunck, The application of spaceborne GPS to atmospheric limb sounding and global change monitoring. *JPL Publ. 94-18*, 147 pp., 1994.

Rocken, C., R. Anthes, M. Exner, D. Hunt, S. Sokolovskiy, R. Ware, M. Gorbunov, W. Schreiner, D. Feng, B. Herman, Y.-H. Kuo and X. Zou; Analysis and validation of GPS/MET data in the neutral atmosphere. *J. Geophys. Res*, 102, No. D25, 29,849-29,866, December 27, 1997.

Ware, R., M. Exner, D. Feng, M. Gorbunov, K. Hardy, B. Herman, Y. Kuo, T. Meehan, W. Melbourne, C. Rocken, W. Schreiner, S. Sokolovskiy, F. Solheim, X. Zou, R. Anthes, S. Businger and K. Trenberth; GPS sounding of the atmosphere from low Earth orbit: Preliminary results. *Bull. Amer. Meteor. Soc.*, 77, 19-40, 1996.

Yunck, T.P., G.F. Lindal, and C.H. Liu, The role of GPS in precise earth observation, paper presented at the IEEE Position, Location and Navigation symposium, Orlando, 1988.

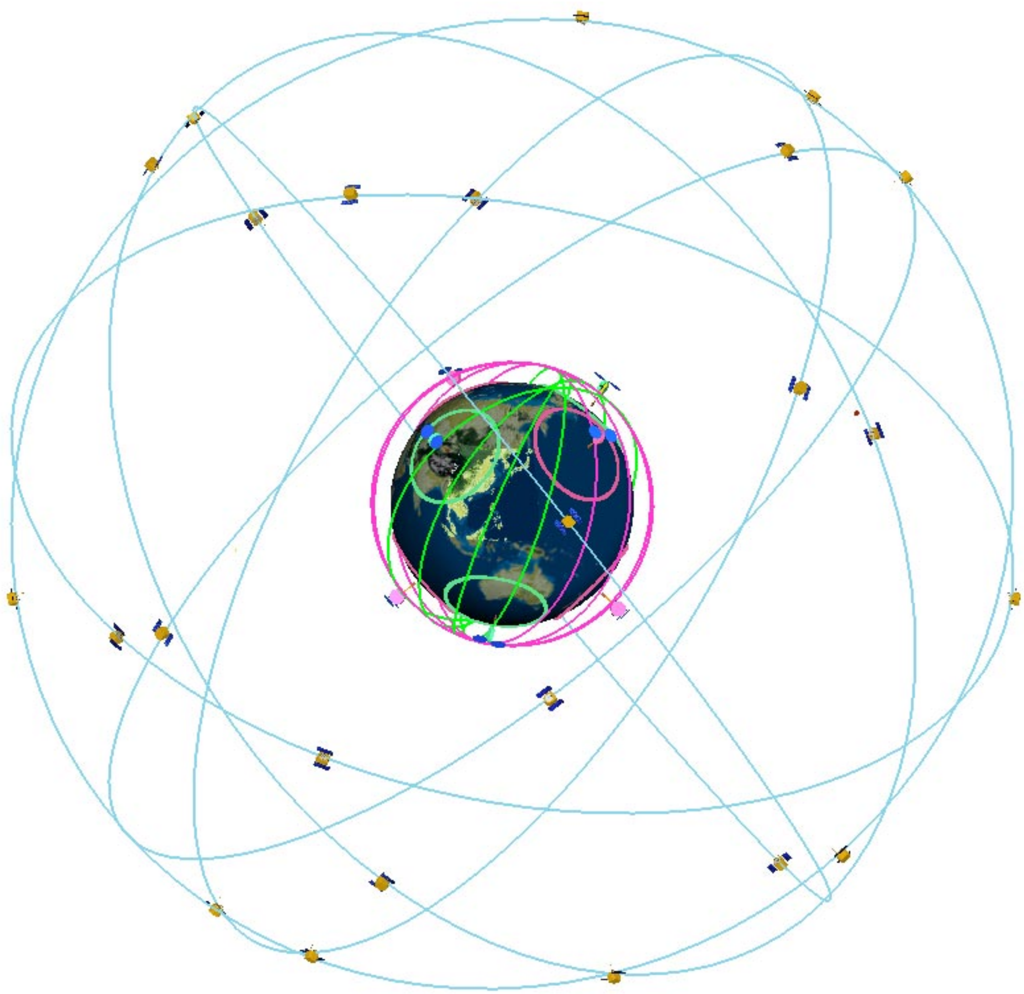
Zou, X., F. Vandenberghe, B. Wang, M.E. Gorbunov, Y.-H. Kuo, S. Sokolovskiy, J.C. Chang, J.G. Sela and R.A. Anthes, A raytracing operator and its adjoint for the use of GPS/MET refraction angle measurements, in press, *J. Geophys. Res.*, 1999.

Figure Captions

Figure 1. Eight micro-satellites orbiting the Earth at an altitude of 800 km (magenta) in the COSMIC Mission. The smaller circles on Earth's surface represent the radio receiving range for the COSMIC satellites. The larger circles (blue) depict 24 GPS satellites orbiting at an altitude of 20,200 km.

Figure 2. The preliminary design of a COSMIC micro-satellite.

Figure 3. A typical COSMIC sounding coverage (green dots, about 4000 profiles) per day. Loci of current operational radiosonde stations (red dots) are also shown for comparison.



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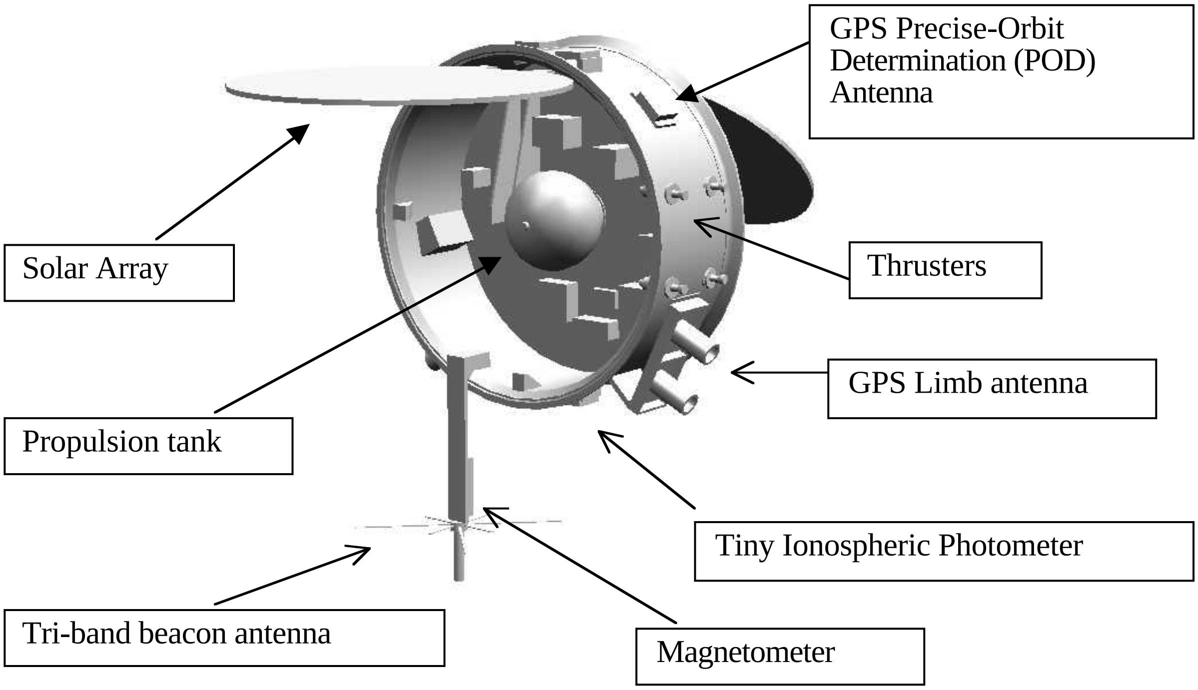

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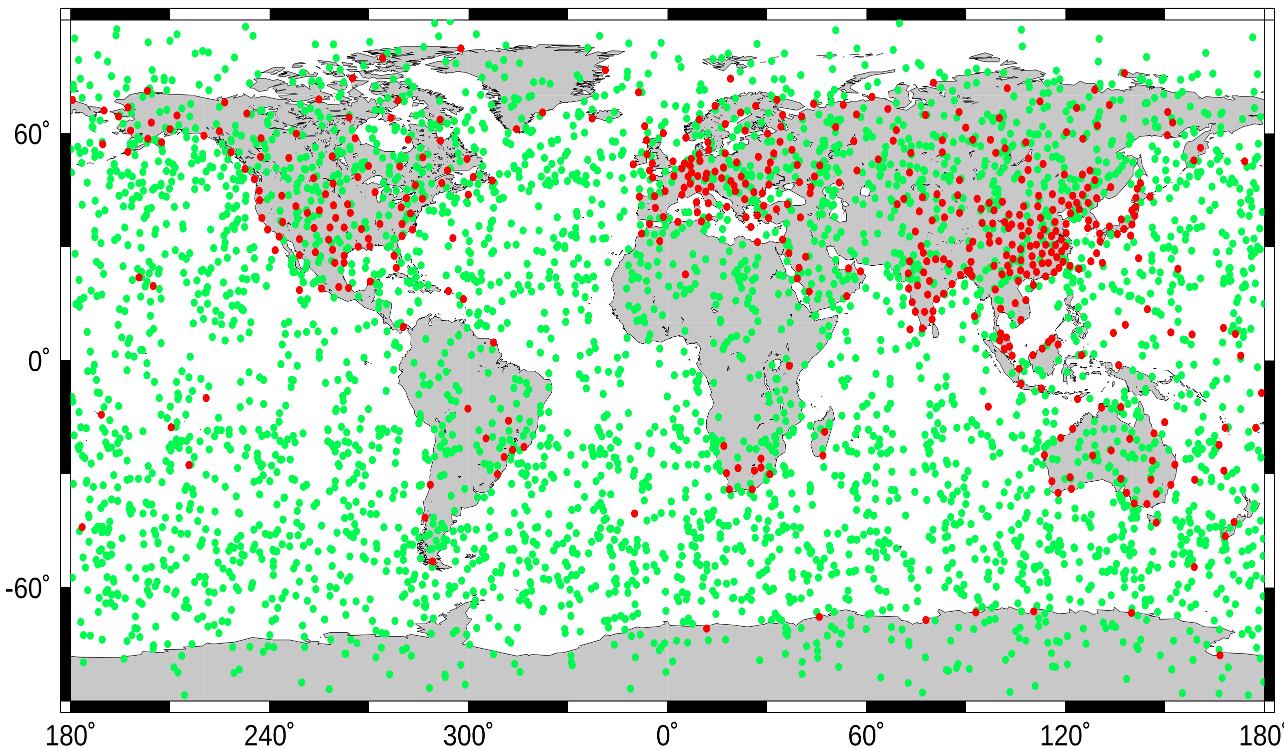

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